Cortical Control of Neural Prostheses

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Abstract

Two additional surgeries were performed during the reporting period. Due to time-varying difficulties with the electrode arrays, work was undertaken to study the effects of electrode tip geometry, impedance measurements, and electrical arc treatments of the microwire arrays. Though we have not solved these difficulties yet, we are making progress toward making improved electrode arrays and increasing our understanding of how to obtain more reliable and stable recordings of cortical unit activity. Many of the units we have recorded to date exhibit patterned activity suggesting that they are directionally tuned to limb endpoint movements. Interestingly, patterned activity is exhibited (in at least one cell) in the left motor cortex when both the right and the left arms are moved.

Work Performed During Reporting Period

1. Motor Cortex Implants

A new, revised surgical implant procedure was followed during the reporting period. In each of the two surgeries performed, two 16-wire arrays were implanted over each cerebral hemisphere of a monkey. Instead of removing a large piece of skull and implanting a cylindrical recording chamber, we cut a longitudinal slot 5 mm wide, 2.2 cm from the midline that was about 5 cm long. This exposed the dura lying over the primary motor, primary sensory and superior parietal cortices.

During the first surgery we tried to stimulate through the exposed dura with a sharp, stainless steel needle. We used anodal shocks in an effort to elicit muscle contractions and accurately identify the shoulder area of motor cortex without removing the dura. However, we were unable to observe any contractions which was likely due to the deep anesthetic state of the animal and the corresponding muscle flaccidity. The idea of mapping the cortical surface with electrical stimulation during surgery was therefore abandoned. Using the central sulcus (visible through the dura), we then inserted the two electrode arrays 1 mm and 3 mm anterior to the sulcus. The electrodes were inserted to a depth of 2.5 mm. No unitary activity was observed during the insertions.

In the next surgery, on the contralateral hemisphere, we used a glass-coated platinum iridium microelectrode to transdurally record single units at different locations along the parasagittal exposure. The isoflurane inhalant percentage was reduced from 3.0 to 2.5 during the recording so that peripheral mechanical stimuli would be more likely to drive the cortical units. We found units clearly driven by light punctate stimuli applied to the skin and hairs of the arm in the posterior and middle portions of the exposure. Manually rotating the joints of the upper extremity drove cortical units in the anterior-middle portions which were anterior of the central sulcus (as visualized through the dura). Electrode arrays were then placed at sites where there was a predominance of shoulder-driven activity. We recorded activity on one of the arrays as it was inserted and fixed the array at a depth where the largest amplitude spikes were found. This was at a depth of about 2 mm.

For both surgeries the electrode insertion procedure was the same. At the desired A-P location along the exposure, the skull defect was widened to about 1 cm. The dura was slit transversely and the electrodes advanced through the opening. After the electrode array pierced the pia, agar was poured around the electrode array to seal the exposed cortex. The two arrays (anterior and posterior) were inserted simultaneously with individual manipulanda (i.e., microdrives) at a rate of 20 microns/minute. Once the arrays were advanced to the desired depth, dental acrylic was placed around the wires, over the agar and the margins of the bone. This technique has been successful in minimizing trauma to the cortical surface without producing noticeable swelling.

2. Summary of Neural Recordings

We have observed a gradual increase in the number of recorded units following each implant surgery (Table 1). In the left hemisphere, during the surgery there was no unitary activity recorded on either the anterior or posterior electrode array. Two weeks after the surgery, two very small spikes (10 μV) were observed on the posterior array. One month after the surgery, six units were recorded on the same array. Presently (two months post-op), we can reliably record eleven units from this array. There has never been any observable activity on the anterior array.

In the right hemisphere, we recorded activity (5 units) on the posterior array the day after the surgery, but this disappeared several days later. Two weeks after the surgery, unit activity began to reappear so that presently (six weeks post-op), we are recording five units with this array. Although unit activity was found during the surgery on the anterior electrode, unit activity has not been observed since.

At least some of the recorded units exhibit directional selectivity as the animal performs the 3D reaching task. Figures 1 and 2 on the following pages illustrate responses of one representative unit recorded from the posterior array in the left hemisphere. The animal completed five trials in each of the eight movement directions. Figure 1 shows the responses associated with movements of the right arm and Figure 2 shows the responses associated with movements of the left arm.

Table 1. Summary of Neural Recordings in Monkey "D". Left hemisphere surgery March 13, 1997; Right hemisphere surgery April 9, 1997.

Week Beginning:	*Left Hemisphere Avg. No. Units*	*Left Hemisphere Amplitude Range*	*Right Hemisphere Avg. No. Units*	*Right Hemisphere Amplitude Range*
March 17, 1997	0	--	--	--
March 24, 1997	1.5	10 μV	--	--
March 31, 1997	0.75	10- 30 μV	--	--
April 14, 1997	4	20-70μV	3	35-75μV
April 21, 1997	5.5	15 -60μV	3.5	30-40μV
April 28, 1997	4.75	30-70μV	3	20-60μV
May 5, 1997	5.75	30-60μV	5.5	15-75μV
May 12, 1997	9	20-60μV	5	15-60μV

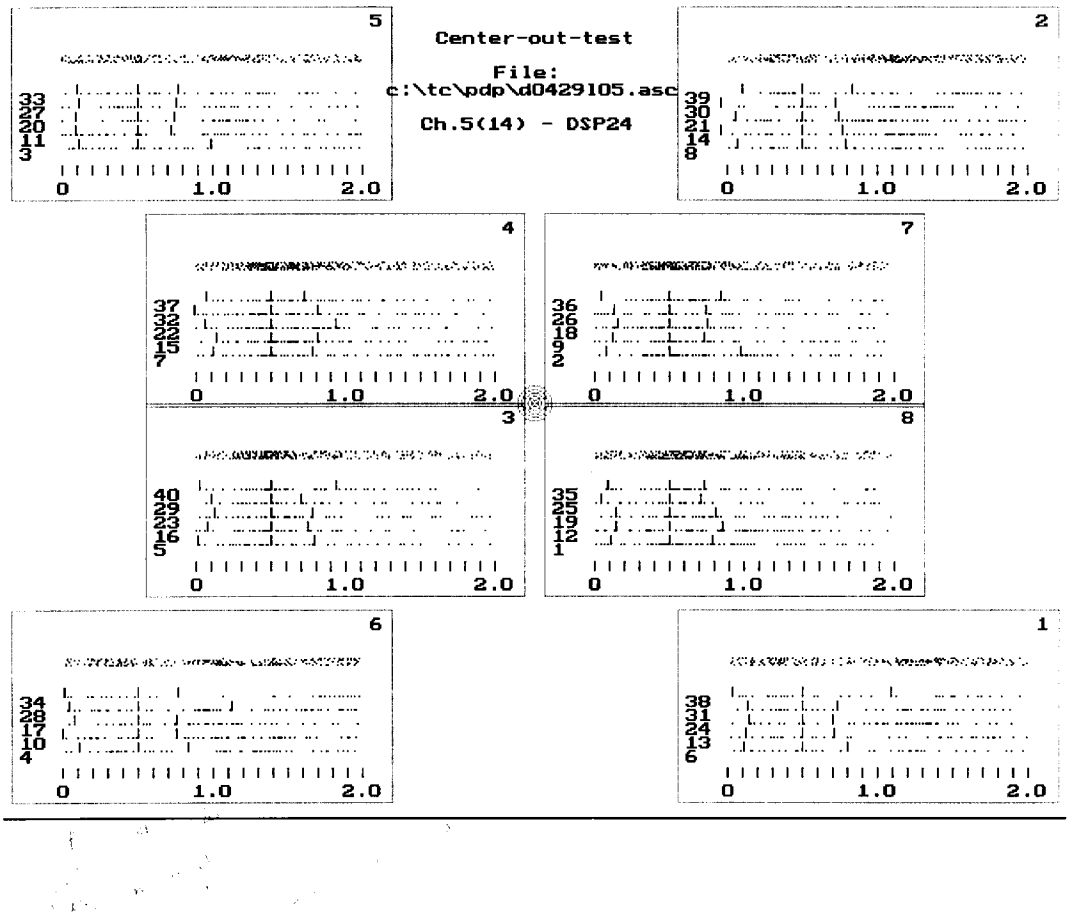


Figure 1. *Raster plots of unit 24 recorded in the left hemisphere of monkey "D" with movement of the right arm (d0429l05.asc). The four central plots represent activity patterns when the monkey moved its hand toward one of the four distal corners of a cube starting from a central position. The four outer plots represent activity when the monkey moved its hand toward one of the four near corners of the same cubic volume. Individual dots in the raster represent a spike recorded during the time course of the movement. The records are synchronized at the instant of movement initiation (the middle tic mark). Firing rates for this unit are greatest during movements toward the distal markers.*

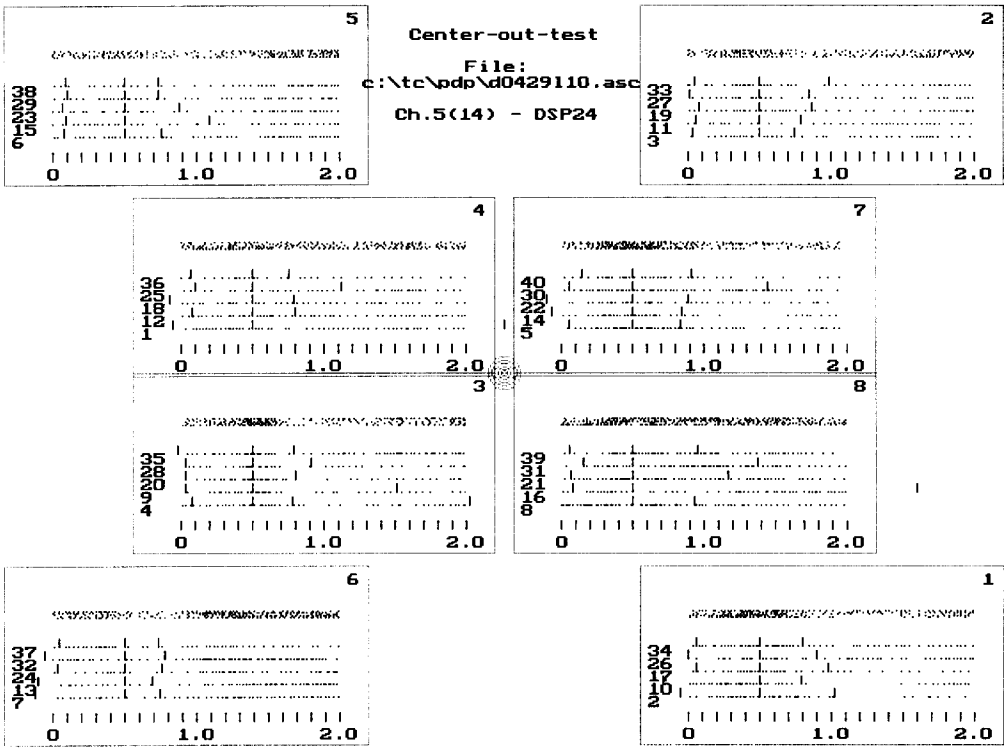


Figure 2. *Raster plots of unit 24 recorded in the left hemisphere with movement of the left arm (d0429l10.asc). Interestingly, the raster plot shows patterned activity in this left hemisphere unit for movements of both the left arm (shown in this figure) and the right arm (shown in Figure 1).*

3. Electrode Impedance Measurements

In an attempt to better understand and predict the recording performance of the wire arrays, we have been monitoring the impedance of the implanted electrodes for several months. We have observed uniform trends of impedance variation, independent impedance shifts, and short durations of impedance stability (Figure 3).

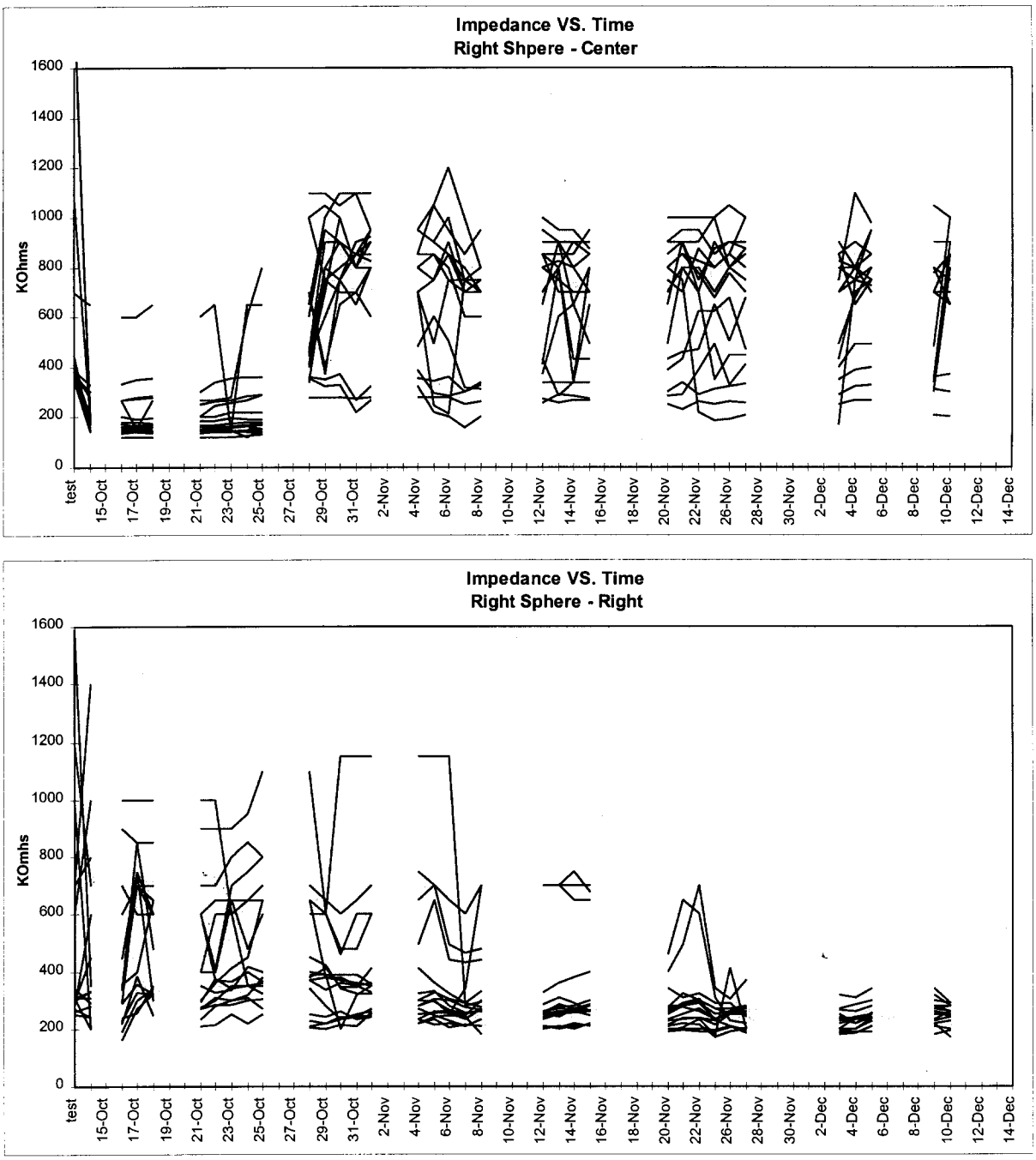
Results show that there are significant and frequent changes in impedance values post-implantation in comparison to control measurements of impedance values, which were taken in a physiological solution prior to implantation for several days. Upon microscopic inspection of these microelectrode arrays, we found inconsistencies in the teflon insulation around the individual wires. A correlation between electrode impedance and electrode tip condition has been found. Electrode tips were examined via light microscopy and the insulation of the individual electrode tips were classified as: (i) flush, (ii) recessed, or (iii) extended (Figure 4). Insulation leakage was present among the flush and recessed conditioned electrode tips, which resulted in low impedance values. In the case of the extended electrode tip condition, insulation overlap or obstruction was observed, which resulted in high impedance values.

In order to correct for the electrode tip condition variability, several different electrode treatments and sterilization techniques have been developed. In the first series of experiments to correct electrode tip variability, a method of heating the electrode-insulation interface was implemented. By arcing a 10,000 volt potential across an air gap near the electrode tip, high enough temperatures were achieved to melt the insulation but leave the metal relatively unaffected (i.e., only slight rounding of the sharper edges was noted). Using an arc instead of a flame (also tried) has the advantage of allowing only one electrode tip to be conditioned at a time, as only a grounded electrode in the array will attract the electrical arc (Figure 6). This treatment resulted in shrinking the insulation back from the tip and shrinking it to the metal surface resulting in lower impedances and less variable electrode impedance values when tested over time in saline.

On April 9, an "arc treated" 16-channel array and an untreated array were implanted into the right hemisphere of Monkey D. Impedance measurements suggested that independent of electrode treatment, there was a significant increase in impedance values approximately ten to twenty days post-implantation. It is suspected that the uniform impedance changes may be due to a local reaction of the immune system resulting from the encapsulation process. These new values have been two to three times more than the initial implantation impedance and remain stable with small fluctuations over a duration of two months (Figure 5).

Uniform changes in impedance can be seen for neighboring electrodes in the array. This suggests that the impedance of the electrodes is affected by the local conditions surrounding individual electrodes. These results suggest the need for further experiments investigating the impedance of local tissue surrounding the individual electrodes in contrast to the impedance of the bulk tissue surrounding the electrode array.

Figure 3. *Impedance values of two 16 channel electrode arrays implanted in the motor cortical area of the right hemisphere of Monkey C over a period of several months. Line segments having the same gray shade depict the impedance of a single wire electrode. The aggregate effect is that the electrodes of the right hemisphere abruptly increased in impedance, while the electrodes of the right hemisphere decreased in impedance over time. We believe that these changes in impedance adversely affect our ability to make stable recordings in the motor cortex.*



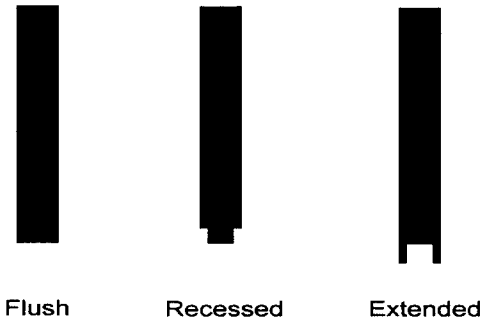


Figure 4.. Electrode Tip Conditions. *There is considerable variability in electrode tip conditions. Through visual microscopic inspection the tips can be classified according to the condition of the insulation relative to the metal surface. These conditions were classified as: insulation flush, insulation recessed, or insulation extended.*

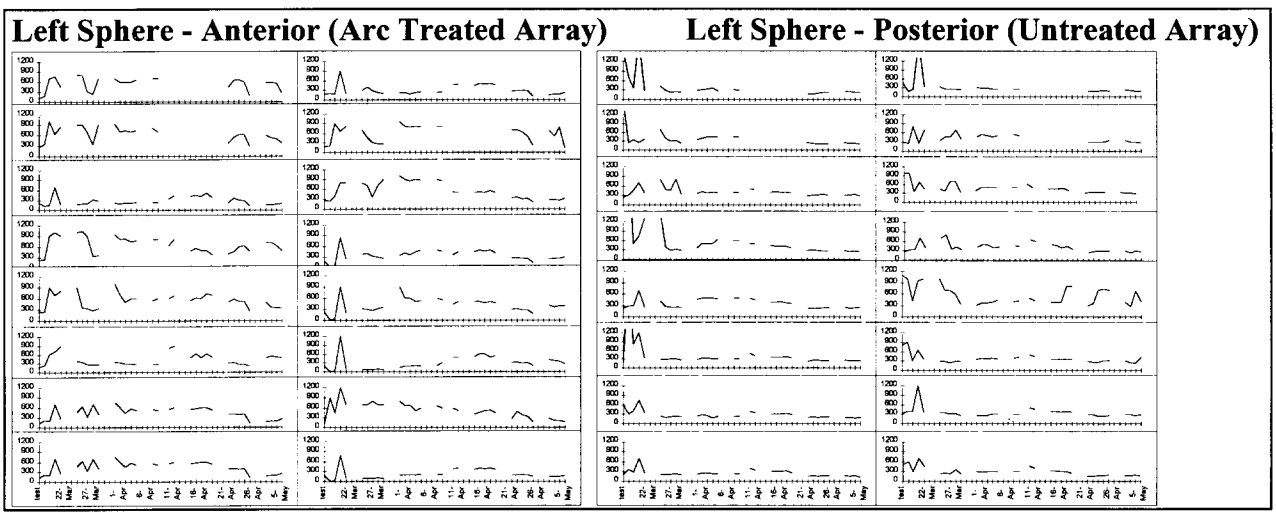


Figure 5. Impedance variations *of "arc treated" and "untreated" electrode arrays over time in Monkey D.*

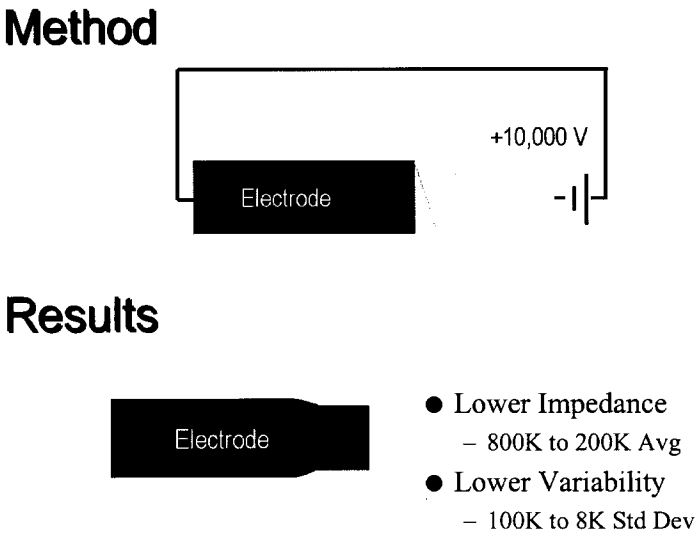
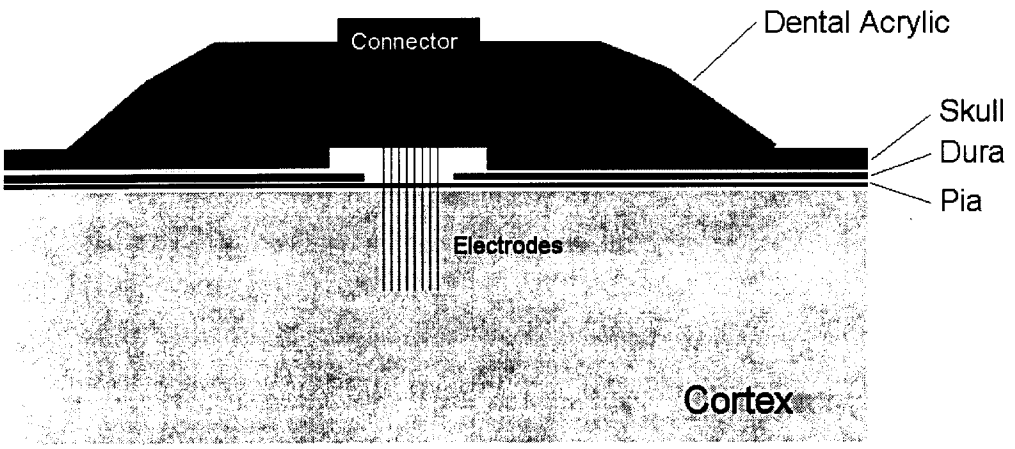


Figure 6. *Arc treatment procedure for modifying the tips of stainless-steel electrodes.*

Figure 7. *Schematic diagram of the electrode-tissue interface.*



From a literature review, a preliminary model of the impedance characteristics of the electrodes as well as the electrode-tissue interface was developed during the reporting period. The model consists of several parts; the resistance of the electrode metal, the capacitance across the electrode insulation, Figure 7 shows a schematic of the electrode-tissue system. Visual inspection allows this system to be broken down into six general components and interfaces that are significant sources of impedance changes. Although each of these areas may have within them multiple impedance sources, the impedance properties within each area all derive from some physical significance specific to that area.

The six areas encountered are: 1. Electrode Shaft, 2. Electrode Insulation, 3. Electrode Tip, 4. Encapsulation Tissue, 5. Bulk Tissue, 6. Reference Electrode. Each part will be analyzed independently and correlated with experimental results before an entire accurate model is considered. The preliminary research and modeling offers insight from which further experiments can be devised to accurately formulate a complete model. This model can then be used for in vivo estimations of physical events occurring during the brain's immunological response to the implant, such as encapsulation and ionic changes in the bulk tissue medium. These experiments may offer a better understanding of the factors that affect the biocompatibility of the implanted electrodes and lead towards more stable and longer life implants. We are currently developing an equivalent lumped-circuit model of this system.

Work Anticipated for Next Reporting Period

Modification of microwire arrays.

We have not had the capability of sterilizing the microwire arrays from NB Labs. The polyethylene glycol (PEG) that is used to stiffen the wires during insertion melts with the moderate heat that is required to dissipate the residual gas after conventional gas (ethylene oxide) sterilization. To date we have cleaned the electrodes prior to implantation by soaking them in an antiseptic such as alcohol. During the next project period, we will stiffen the arrays with small-diameter plastic rods rather than PEG. Three rods are attached to the connector and a small patch of dental acrylic placed approximately 3 mm from the end of the electrodes. After the array is inserted, the electrode will be fixed by cementing this acrylic patch to the nearby bone with additional dental acrylic. The rods will then be removed to facilitate orienting the connector on the head. These electrodes will then be sterilized in an autoclave.

A second electrode modification will involve constructing the microwire arrays with 25-micron, polyamide-insulated tungsten wires rather than the 50-micron, teflon-insulated stainless steel wires that are currently used. We purchased and sent this wire to Larry Andrews at NB Labs and he is currently fabricating the electrodes for us to our specifications.

A third electrode modification will involve constructing less densely packed arrays consisting of wires spaced approximately 800 microns apart rather than the current 400 microns.

Surgical Implants and Neural Recording

We expect to implant both hemispheres of an additional animal during the next reporting period and to continue daily recording and behavioral training sessions in both of our current animals.

Computer Simulation of Prosthetic Limb Movement and Interfacing of the Robot

We have implemented a new control algorithm to simulate the control of an artificial or paralyzed rhesus monkey limb. The new algorithm is based on the pseudoinverse optimal control algorithm, but is speeded up by reducing the number of degrees of freedom to control. We intend to test the algorithm by comparing the outputs (limb angle trajectories) with the monkey's freely chosen limb angles during the center->out movements. Our control input (the intended vector velocity of the limb endpoint) as we expect will be someday delivered by the Population Vector Algorithm, will be passed as three scalar quantities into the computer via a serial input port (e.g., RS-232 or a mouse port). If time and progress permits, we will also begin to implement the real-time control of the Zebra-ZERO robot for eventual use as the device which will be interfaced to the monkey motor cortex.